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28 Nov 2012 – 2 Dec 2012

# **Directionally Solidified Aluminum – 7 wt% Silicon Alloys: Comparison of Earth and International Space Station Processed Samples**

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## **This Investigation is a Collaborative Effort with the European Space Agency (ESA) Program:**

***Microstructure Formation in Castings of Technical Alloys under  
Diffusive and Magnetically Controlled Convective Conditions (MICAST)***

**The MICAST Microgravity Research Program Focuses on:**

- A systematic analysis of the effect of convection on the microstructural evolution in cast Al-alloys.
- Experiments that are carried out under well defined processing conditions.
- Sample analysis using advanced diagnostics and theoretical modeling.

→ The MICAST team investigates binary, ternary and commercial alloys based on the Al-Si system.



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## Intent

### Conduct a Thorough Ground-based Investigation

- **Utilize Aluminum – 7wt. % Silicon Alloys**
  - ◆ Directionally Solidify Samples having an Initial Aligned Dendritic Array
  - ◆ Evaluate the Dendritic Microstructure ( $\lambda_1, \lambda_2, \lambda_3, d$ ) as a function of the Steady-State Processing Conditions ( $V, G, C_0$ )

### Use the Above for Comparison to Limited # of DS $\mu g$ Samples

- **Partially melt and Directionally Re-Solidify terrestrially grown dendritic mono-crystals of Al-7 wt% Si (9-mm dia, 25 cm long) in microgravity.**



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## Outline

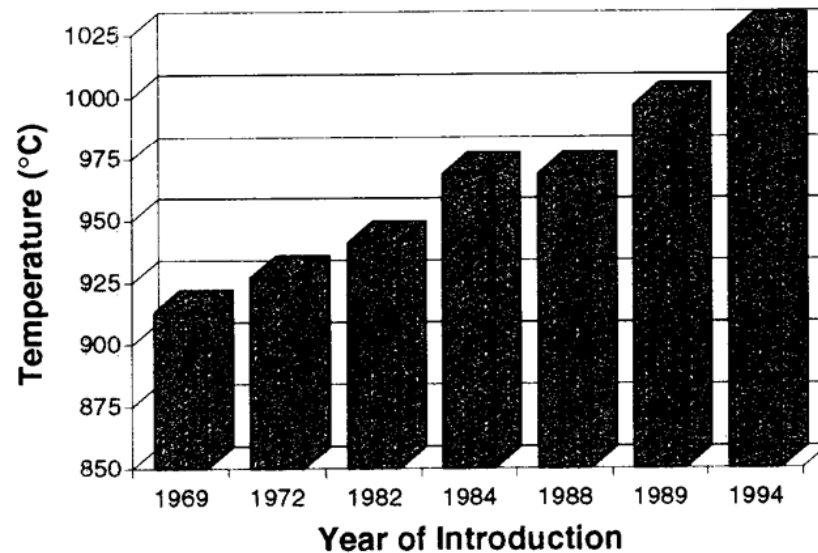
- Microstructural Considerations
- Expectations
- Ground-based Results
- Microgravity Results
- Comparative Comments



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# Microstructural Considerations

## Why Directional Solidification?



Bar chart showing the changes in temperature capability of cast turbine blade alloys as a function of time. The first three alloys in the series are equiaxed, conventional cast. The next one is a monocrystal alloy. The next is a directionally solidified alloy with comparable performance at lower cost. The last two are monocrystal alloys.

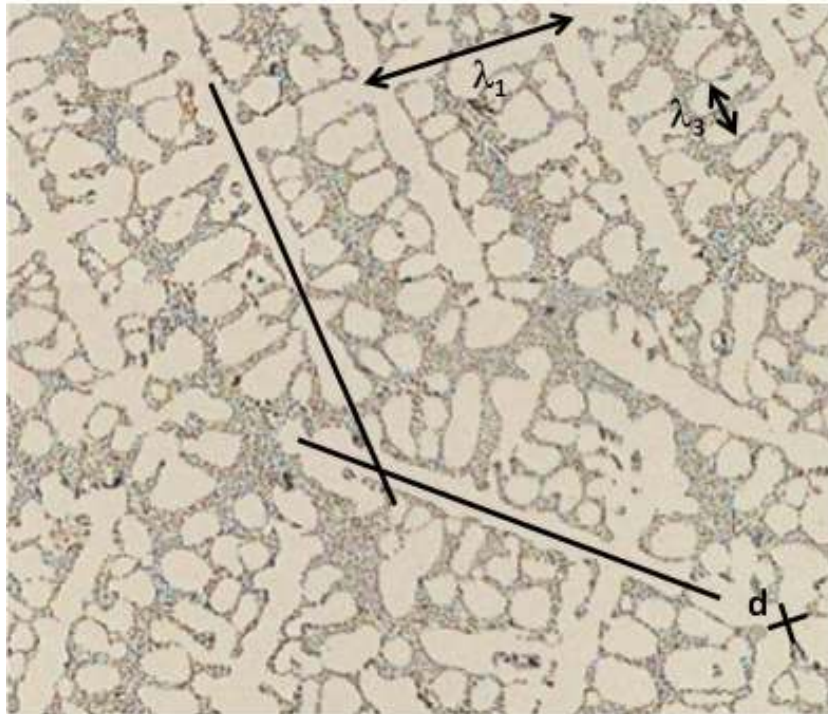
J.C. Williams: Phil. Trans. R. Soc. Lond. A (1995) 351, p. 435.



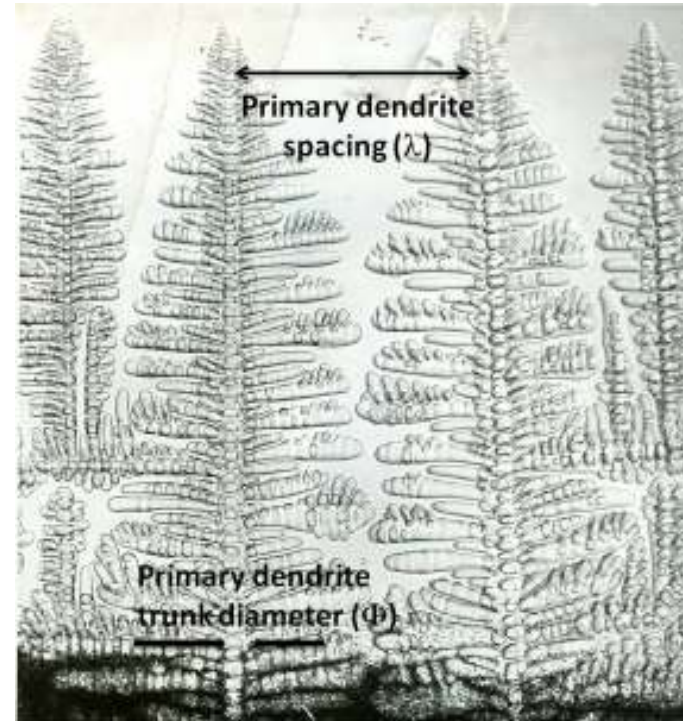


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## Microstructural Considerations: Evaluation



$\lambda_1$ , Primary Dendrite Arm Spacing  
 $\lambda_3$ , Tertiary Dendrite Arm Spacing  
 $d$ , Primary Dendrite Trunk Diameter  
Relative Dendrite Grain Orientation



Statistically Compile and Relate to  
Solidification Processing Conditions of:

- Growth Velocity ( $V$ )
- Temperature Gradient ( $G$ )
- Alloy Composition ( $C_o$ )



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## **Expectations**

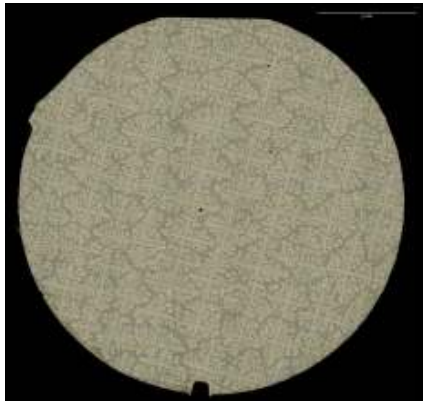
### **Solidification Processing in a Microgravity Environment**

- Advantages:**    **Minimize Thermo-Solutal Convection**  
                         **Minimize Buoyancy Effects**
- Intent:**            **Produce Segregation Free Samples Grown Strictly**  
                         **by Heat Transfer and Solute Diffusion**
- Purpose:**           **Better Understand the Relationship between**  
                         **Processing – Microstructural Development**
- Application:**    **Maximize Material Properties**



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## Microgravity Processing



Al- 7 wt.% Si



Sample Cartridge

ESA Low Gradient  
Furnace (LGF) Insert



Microgravity Science Research  
Facility (MSRF) Aboard the ISS





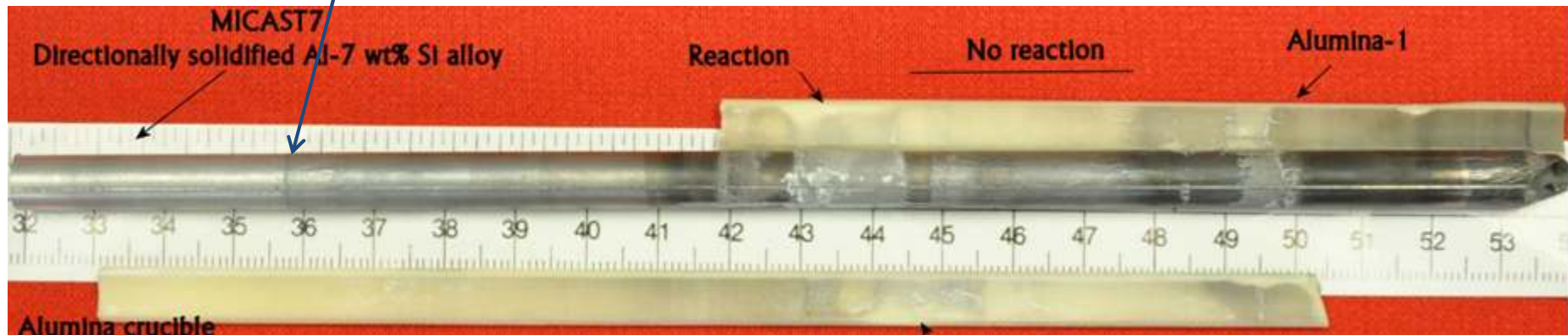
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## Microgravity Processed Sample MICAST 7



Eutectic Melt Back  
/ Isotherm

X-ray radiograph of MICAST7



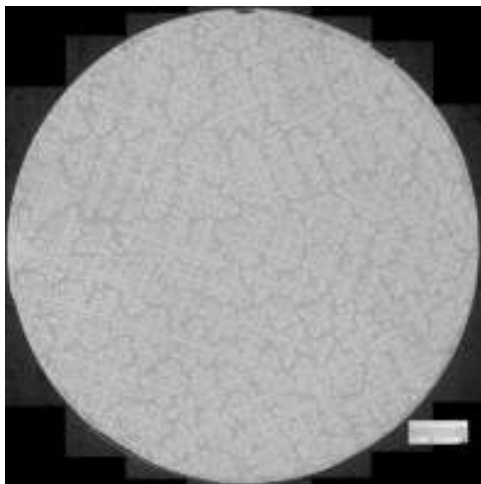
No terrestrial samples which are processed in LGF or SQF equivalent hardware  
under  $R$  and  $G_L$  conditions which are identical to MICAST6, MICAST7



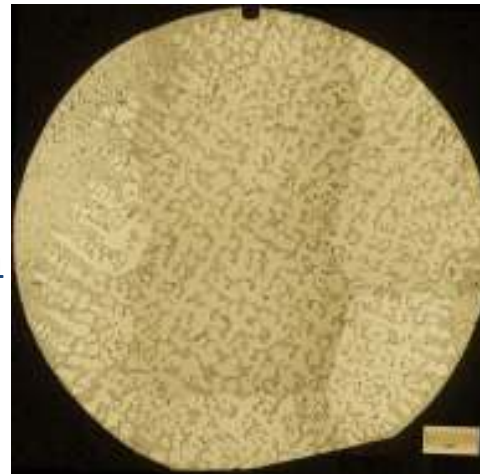
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## Microstructural Comparison: Earth and Microgravity

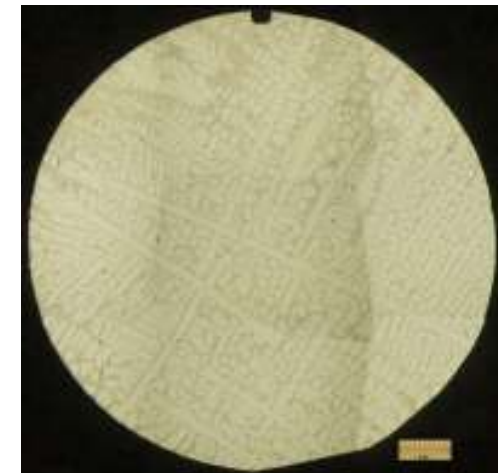
Al – 7 wt. % Si



Terrestrial:  
 $G = 15 \text{ K cm}^{-1}$



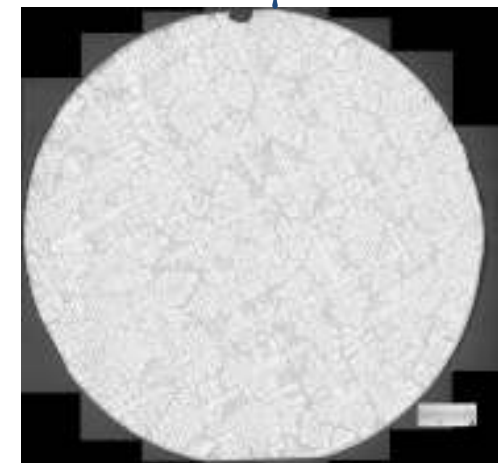
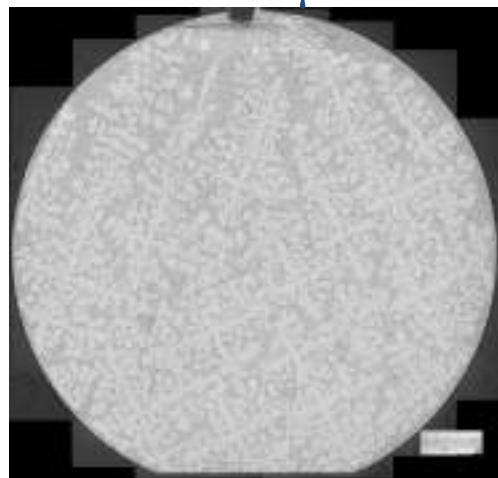
$V = 5 \mu\text{m s}^{-1}$



$V = 50 \mu\text{m s}^{-1}$

MICAST6 Seed:  
 $V = 41 \text{ K cm}^{-1}$ ,  
 $G = 22 \mu\text{m s}^{-1}$

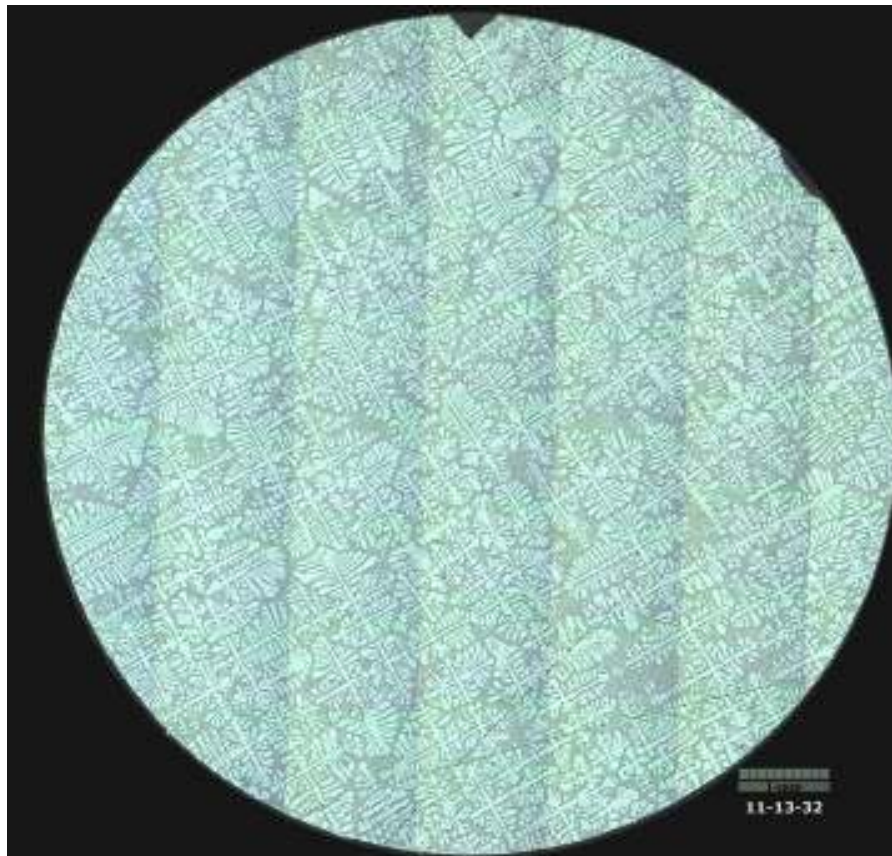
MICAST6:  
 $G = 20 \text{ K cm}^{-1}$



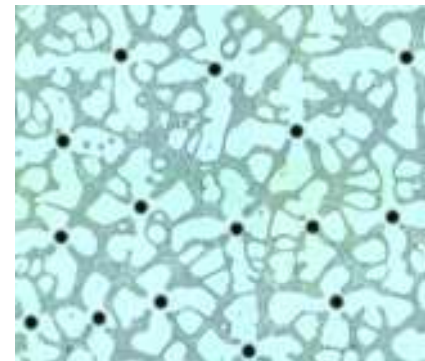


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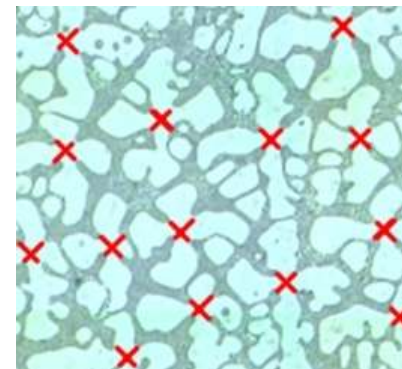
## Microstructural Analysis of Directionally Solidified Al -7 wt. % Si Alloy Samples



Terrestrial:  $G_L = 41 \text{ Kcm}^{-1}$ ,  
 $V = 85 \text{ mm s}^{-1}$



1) Primary Dendrite Arm Spacing



2) Primary Dendrite Trunk Diameter

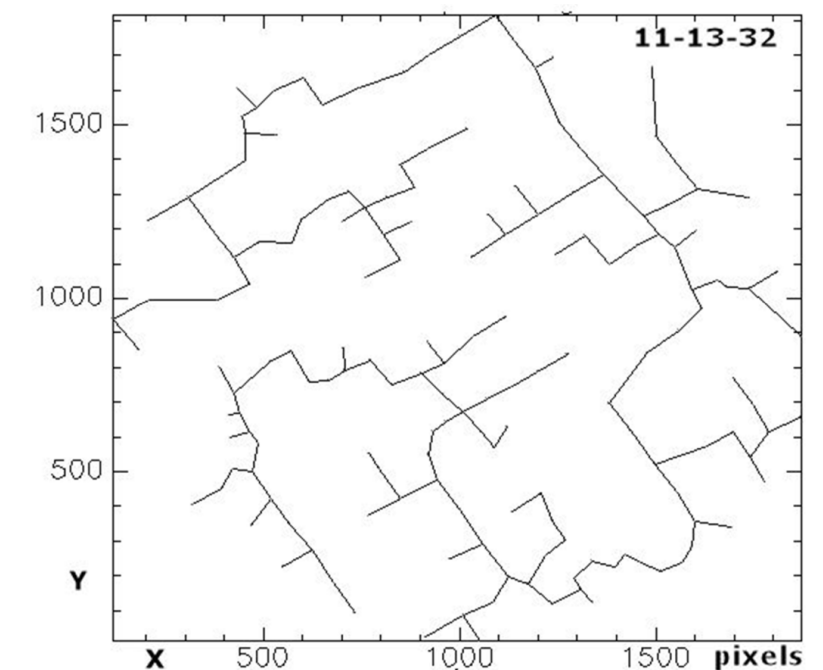
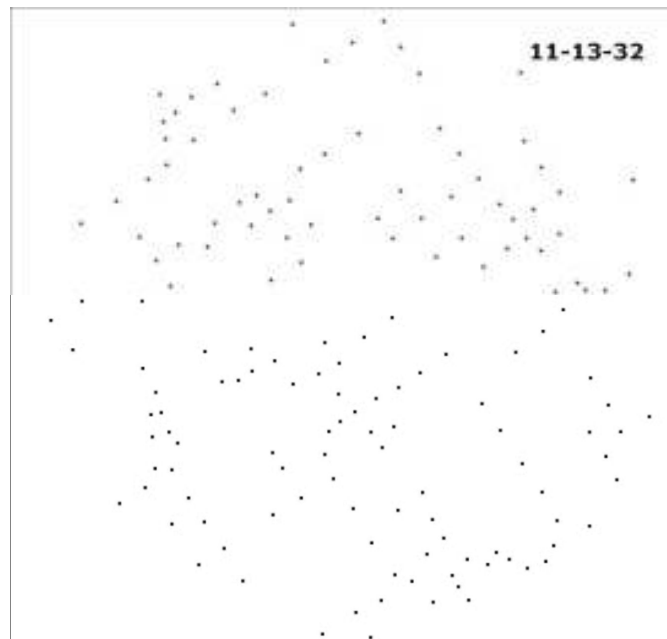




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## Primary Dendrite Arm Spacing ( $\lambda_1$ )

Which primary dendrite arm spacing ( $\lambda_1$ ) to use?



1) Geometrical Spacing:  $\sqrt{A/(N-1)} = 623 \mu\text{m}$

3) Nearest neighbor spacing =  $368 \pm 126 \mu\text{m}$

2) Minimum Spanning Tree:  
Spacing =  $412 \pm 138 \mu\text{m}$

→ Theoretical models predict *nearest neighbor spacing*



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## Theoretical Models for Primary Dendrite Arm Spacing

$$(m_l G_c^t - G_t) / (4\pi^2 \Gamma T_m / r_t^2) = 1 \text{ for small } R r_t / 2D_l$$

$$r_t = - \frac{G_L \lambda_1^2}{4\sqrt{2} [m_L C_t (1-k) + \frac{D_L G_L}{R}]}$$

	<u>Analytical</u>	<u>Numerical</u>
Tip radius:	Trivedi (1980)	<a href="#">Hunt-Lu (1996)</a>
Primary spacing:	<a href="#">Trivedi (1984)</a>	<a href="#">Hunt-Lu (1996)</a>
Trunk diameter:	None	

### Physical Properties for Al- 7 wt% Si

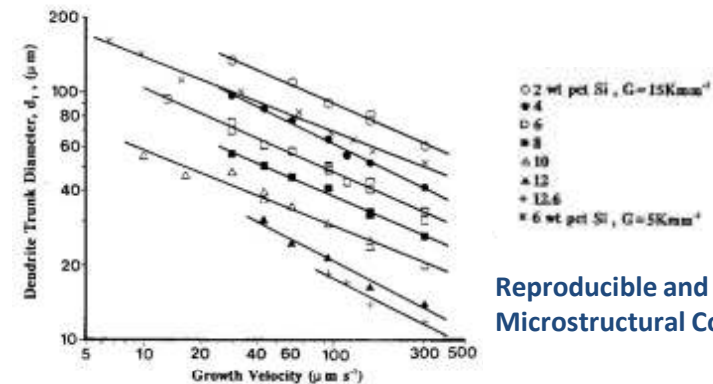
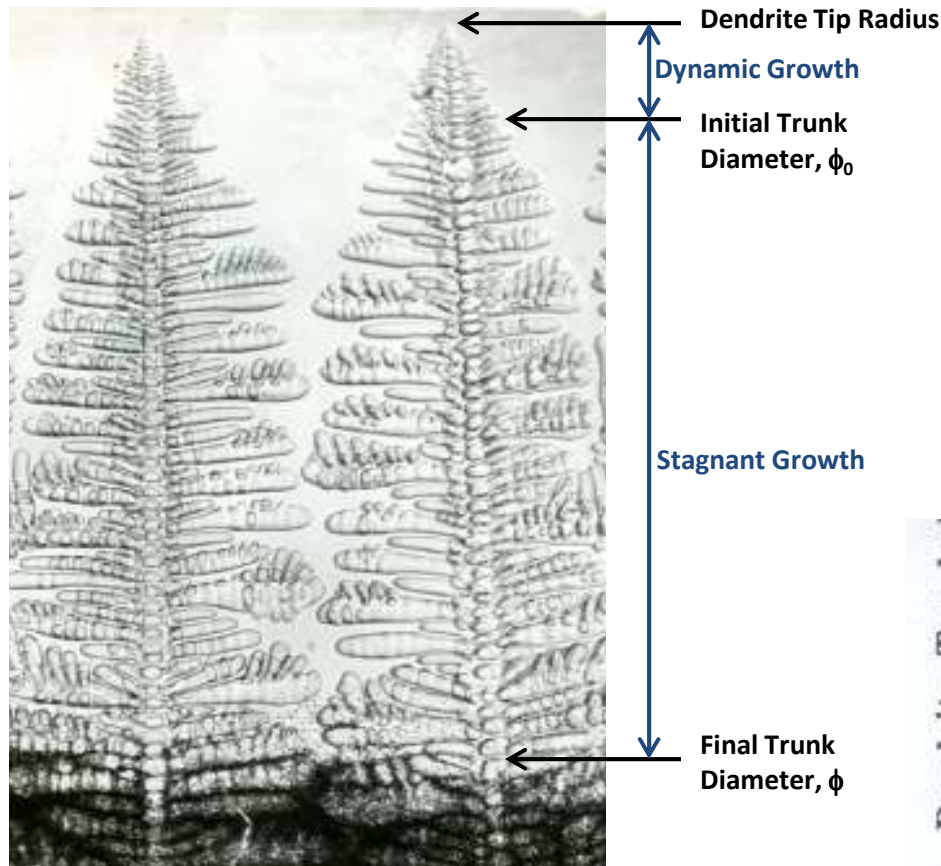
Co	7 wt% Si	
$m_l$	-6.31 K/ wt% Si	Metals Handbook, vol. 8 (1973)
$k$	0.1	
$\Gamma$	0.196 $\mu\text{m K}$	Gunduz and Hunt (1985)
$D_l$	$4.3 \times 10^{-9} \text{ m}^2/\text{s}$	(Poirier compilation)



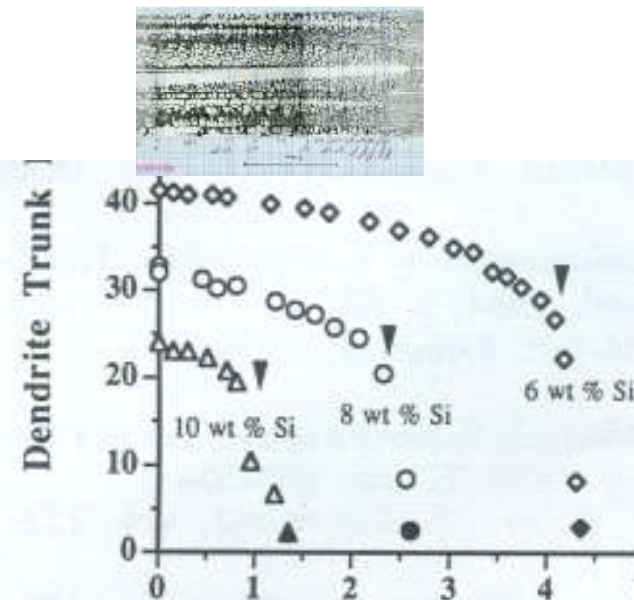


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## Primary Dendrite Trunk Diameter ( $\phi$ )



Reproducible and Predictable  
Microstructural Constituent



Trunk Diameter Rapidly Increases Until Diffusion Fields Overlap ( $\blacktriangledown$ )



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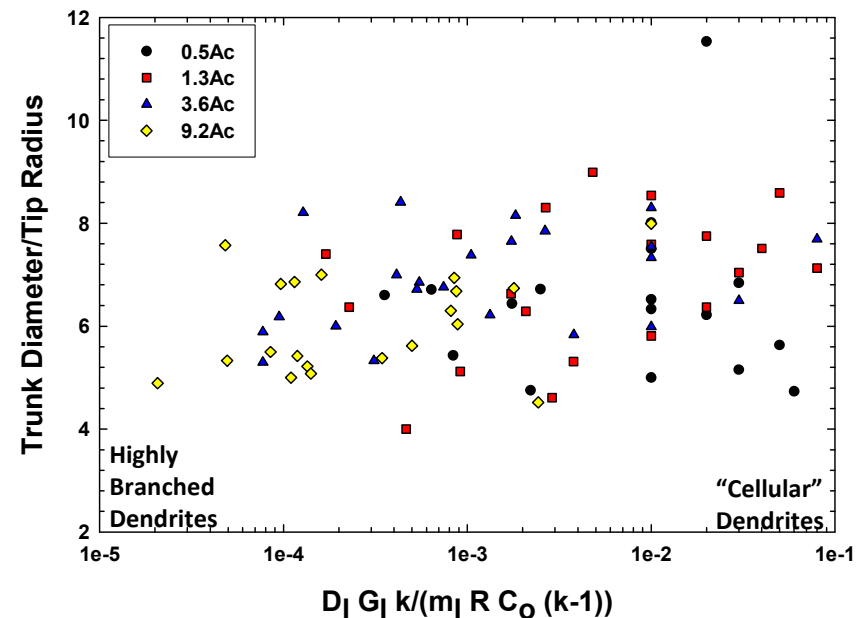
# Primary Dendrite Trunk Diameter ( )

## “Initial” Trunk Diameter ( $\phi_0$ ) Determination

### Primary Dendrite Tip Radius

$$R_{Tip}^2 = \frac{4 \pi^2 D \Gamma}{\Delta T_0 k V}$$

Fundamental of Solidification, Kurz and Fisher, Trans Tech, 1992



Esaka (1986 Ph.D. Thesis) Measured  $\phi_0$  from  
Succinonitrile-Acetone “alloys” grown at  
different V and  $G_L$ .

$$\phi_0 = 6.59 \pm 1.3 R_{tip}$$

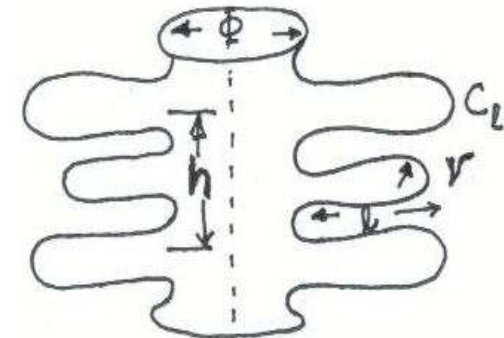


## Primary dendrite trunk diameter ( $\phi$ ) model

After  $\phi_0$  the trunk diameter increases via dissolution of secondary arms and re-deposition on the trunk until the eutectic reaction.

### Assumptions:

1. Kirkwood model (1985) of ripening applies.
2. Secondary arm melts back because of its curvature.
3. Mass of the melted arm deposits on trunk surface where there is negative curvature.



Melting rate of an  
arm of length,  $l$

$$\frac{dl}{dt} = \frac{4 D_l \Gamma}{m_l C_l (1 - k) r^2} \quad (1)$$

$$\pi \phi h \frac{d\phi}{2 dt} = 4 \left( \pi r^2 \frac{dl}{dt} \right) \quad (2)$$

$$C_l = C_o + R G_m t / m_l \quad (3)$$

$$\phi^2 \frac{d\phi}{dt} = 32 \frac{D_l \Gamma}{m_l (1 - k) \left( C_o + \frac{R G_m t}{m_l} \right)} \quad (4)$$

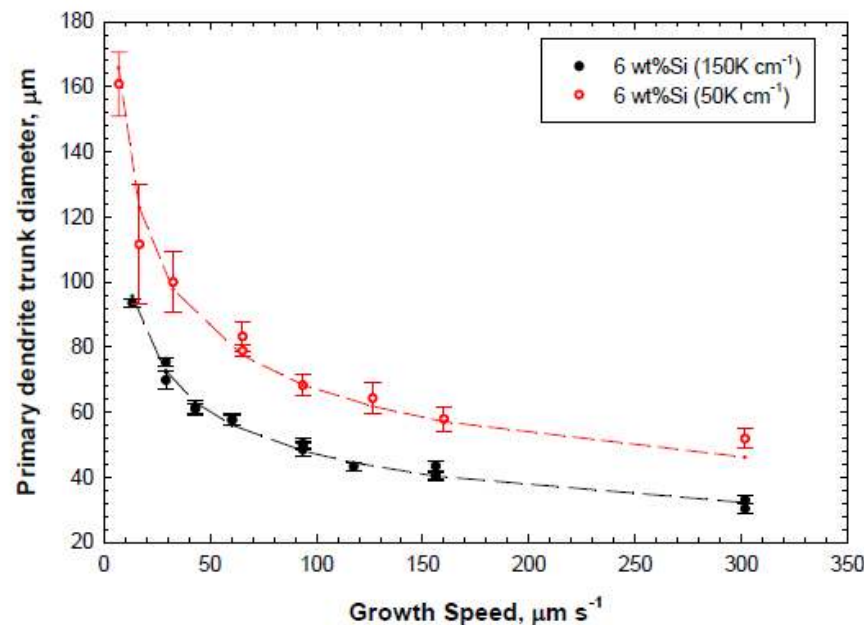


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## Primary dendrite trunk diameter ( ) model

$$\phi^3 = 96 \frac{D_l \Gamma}{R G (1 - k)} \ln \left\{ \frac{\left(1 + \frac{R G t}{m_l C_o}\right)}{\left(1 + \frac{R G t_o}{m_l C_o}\right)} \right\} + \phi_0^3$$

Mushy Zone Freezing Time  $\sim m_l(C_E - C_o)/RG_m$





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**Primary Dendrite Arm Spacing ( $\lambda_1$ )**  
**Primary Dendrite Trunk Diameter ( $\phi$ )**

**Comparison of Earth and ISS Processed Samples  
with Theoretical Models**

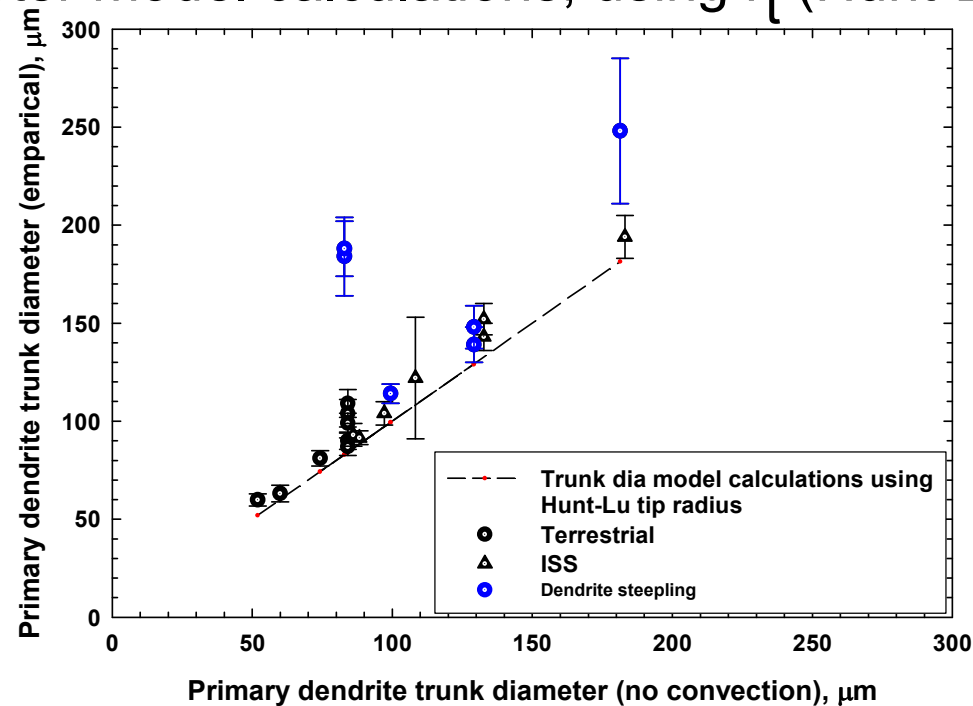






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Primary dendrite trunk diameter as compared to trunk  
diameter model calculations, using  $r_t$  (Hunt-Lu)



- ISS-DS: Good agreement with predictions from the trunk-diameter model.
- Terrestrial DS ("Not Steeped") : Good agreement with predictions from model.
- Terrestrial DS ("Steeped"): Convection increases trunk diameter.



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## Conclusions

- Primary dendrite arm spacings of Al-7 wt% Si alloy directionally solidified in low gravity environment of space (MICAST-6 and MICAST-7: Thermal gradient  $\sim 19$  to  $26 \text{ K cm}^{-1}$ , Growth speeds varying from  $5$  to  $50 \mu\text{m s}^{-1}$ ) show good agreement with the Hunt-Lu model.
- Primary dendrite trunk diameters of the ISS processed samples show a good fit with a simple analytical model based on Kirkwood's approach, proposed here.
- Natural convection,
  - decreases primary dendrite arm spacing.
  - appears to increase primary dendrite trunk diameter.
- Need more samples processed in Microgravity



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## Acknowledgments

This investigation is supported by NASA Grant NAS8-02060. Appreciation is expressed to Dr. Men G. Chu, Technical Fellow-Solidification Technology, ALCOA Technical Center, Pittsburgh, PA . Support from the Materials and Processing Laboratory of the Marshall Space Flight Center is also greatly acknowledged.